Earth's energy imbalance from the ocean perspective

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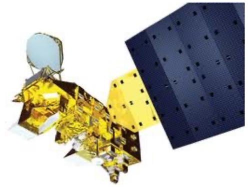
CERES STM, Oct 13, 2021

EEI = Global long-term mean Net Radiative flux at TOA



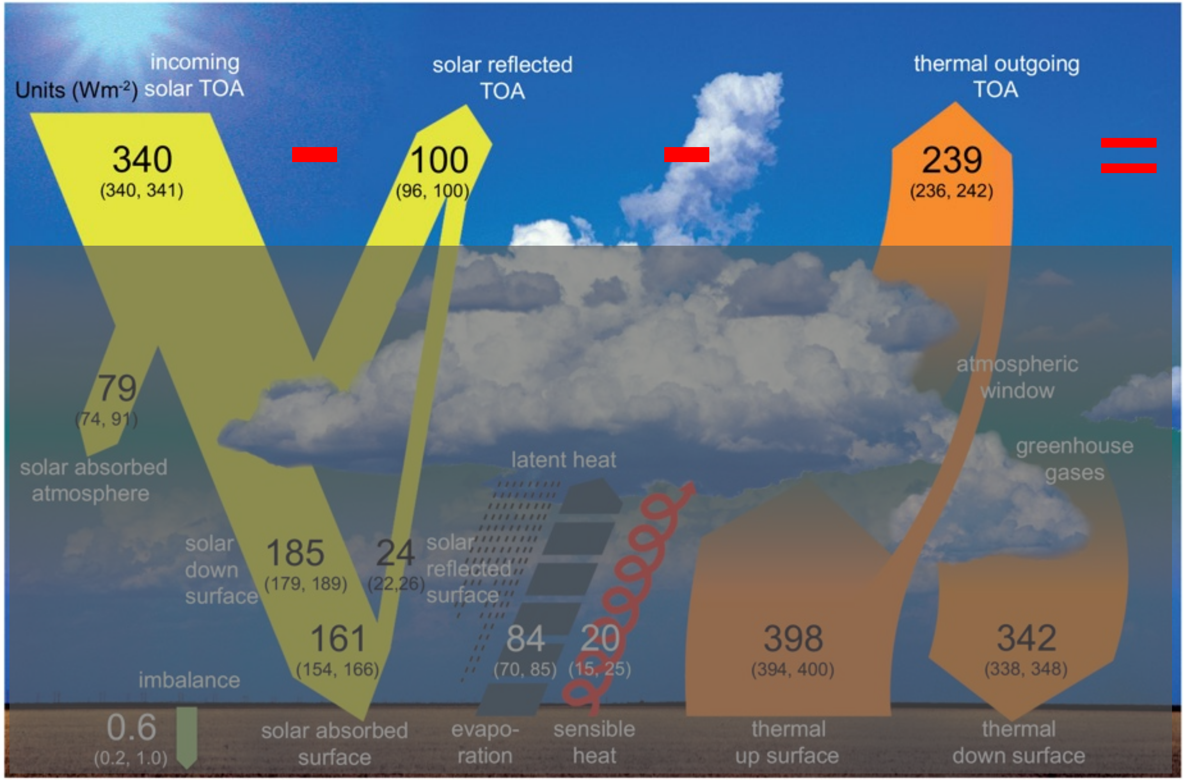
CERES EBAF & Libera

Clouds and Earth's Radiant Energy System

SORCE & TSIS

Solar Radiation and Climate Experiment

Total and Spectral *Solar* Irradiance Sensor



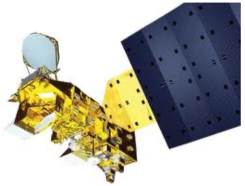
$\sim 0.7\ Wm^{-2}$

(Johnson et al., 2016)

Note: This number does not originate from TOA radiation data!

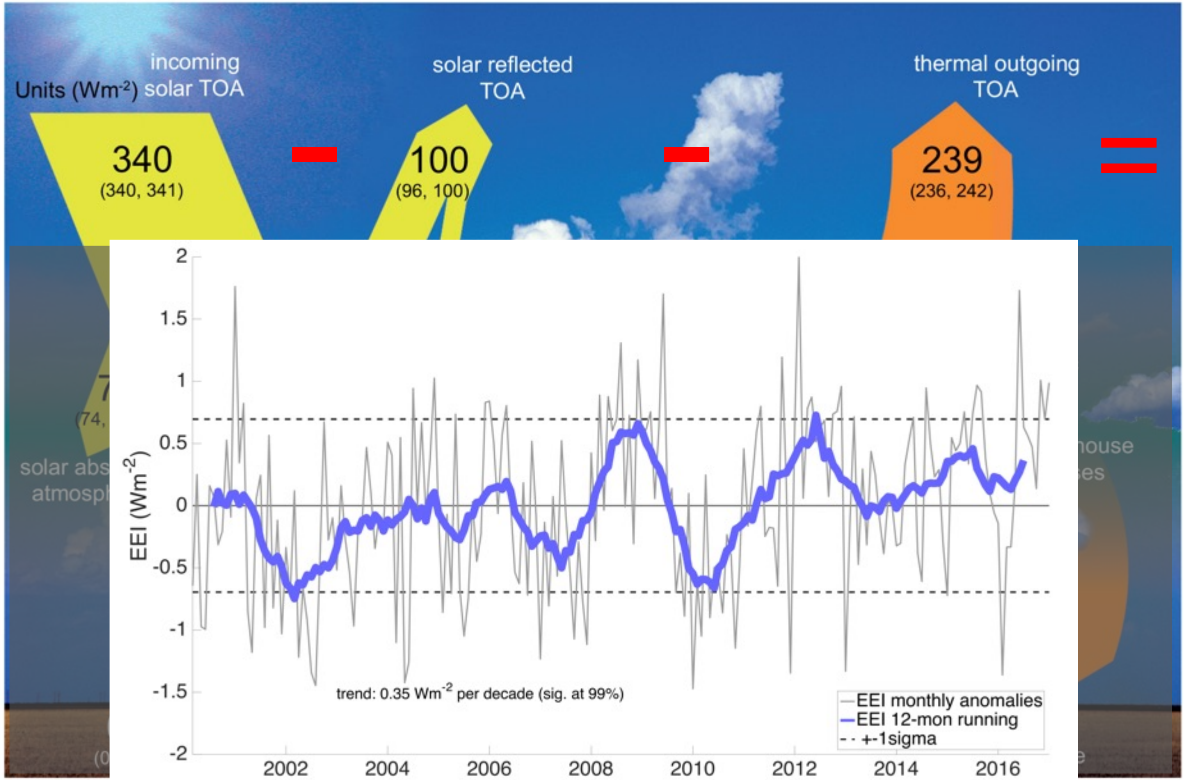
Updated from IPCC AR5 / Wild et al. 2013, 2015 Climate Dynamics

EEI = radiative forcings – radiative feedbacks



CERES EBAF

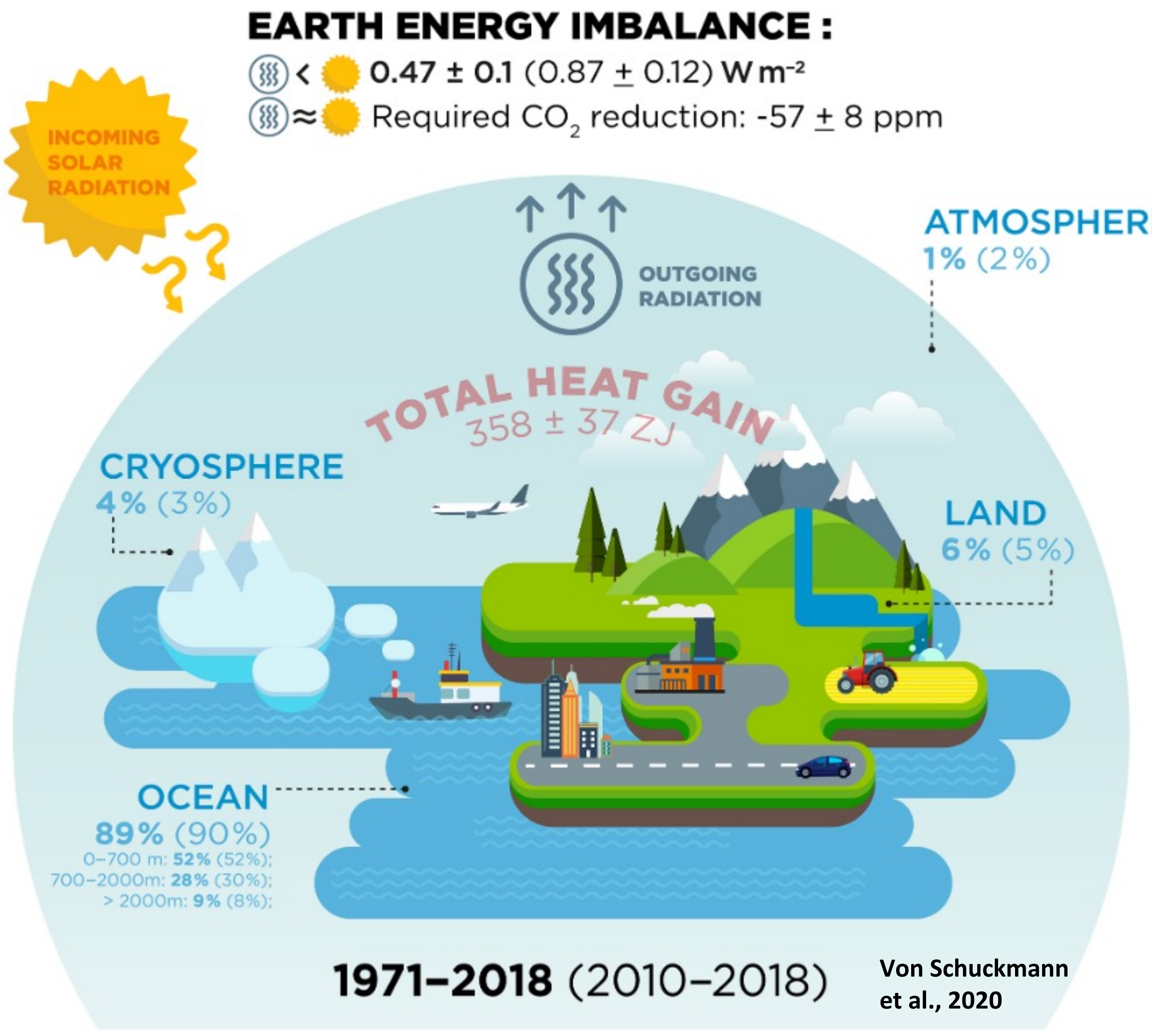
SORCE & TSIS



~0.7 Wm-2

global long-term mean 2005-2015

EEI variability reflects natural and anthropogenic radiative effects on multiple time scales



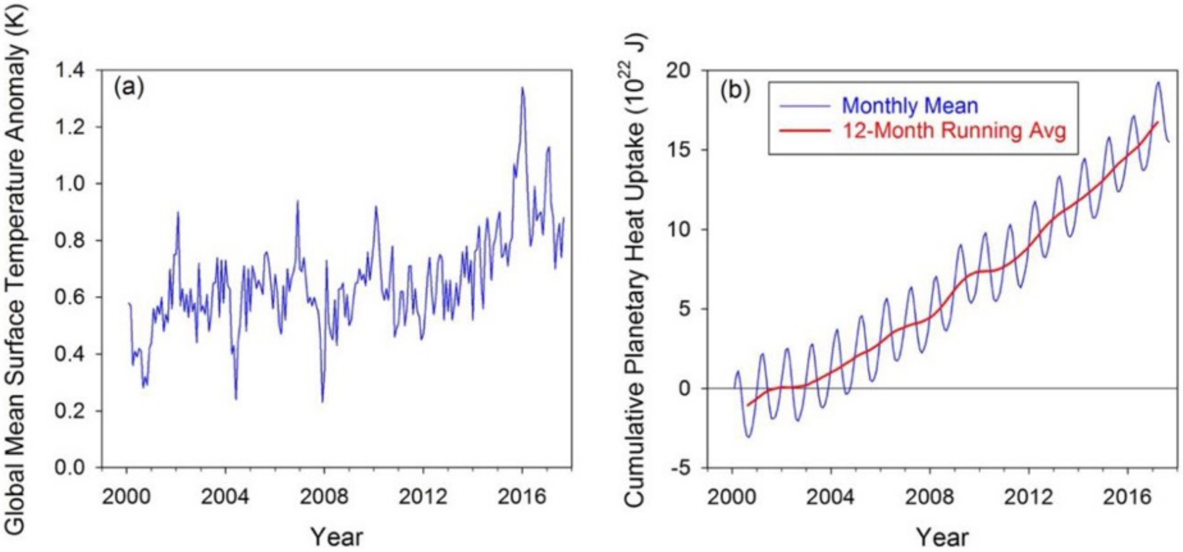
EEI = rate of global heat content change

EEI = heat that melts ice, expands ocean, warms the atmosphere and the land

Von Schuckmann et al., 2020

jpl.nasa.gov

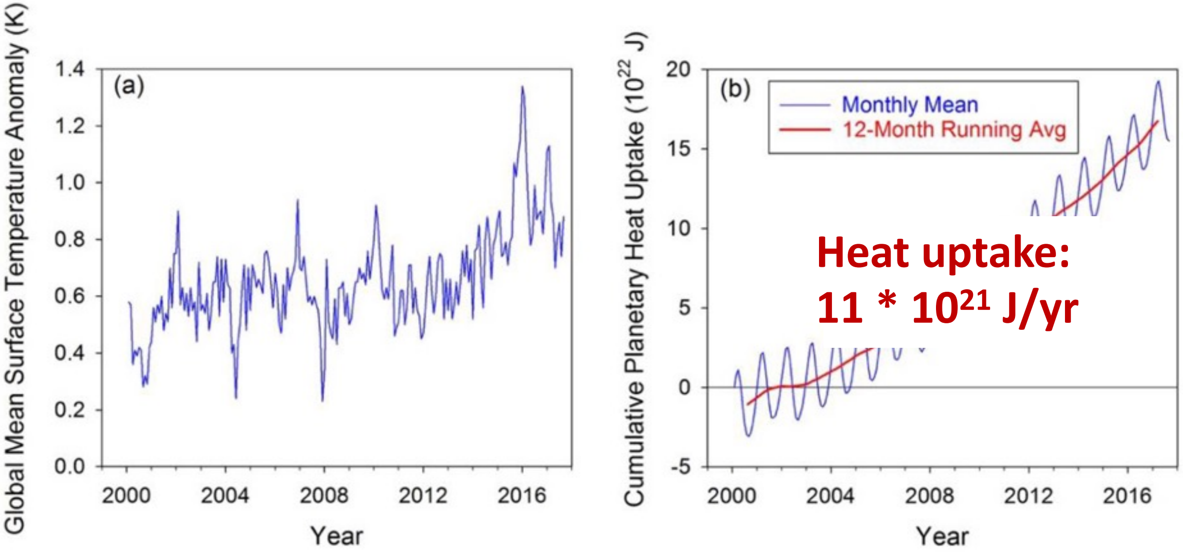
EEI is the *true* rate of global warming/energy accumulation



(**a**) NASA Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) global mean surface air temperature anomaly relative to 1951–1980 climatology and (**b**) Clouds and the Earth's Radiant Energy System (CERES) cumulative planetary heat uptake for March 2000–September 2017.

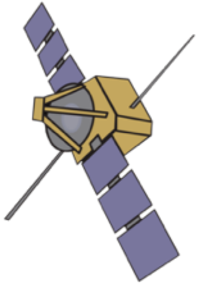
Loeb et al., 2018

EEI is the *true* rate of global warming/energy accumulation



Annual mean heat uptake (= EEI ~0.7 Wm^{-2}) is 18 times the annual energy consumption of the world's population ($6*10^{20}$ J)

It is difficult to measure EEI directly



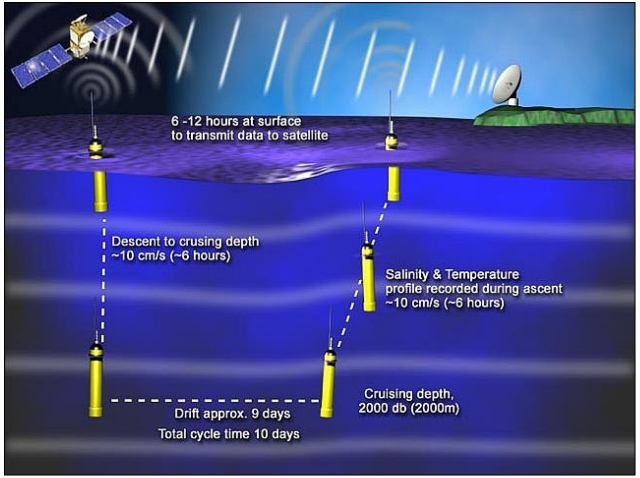
- TOA radiometry: Clouds and Earth's Radiant Energy system (CERES)
  - Uncertainty (calibration, radiation flux retrieval) >> 1 Wm^{-2}
  - Un-anchored, EEI as residual of TOA fluxes would be 4 Wm^{-2}
  - **We cannot estimate EEI directly from the TOA radiation budget**

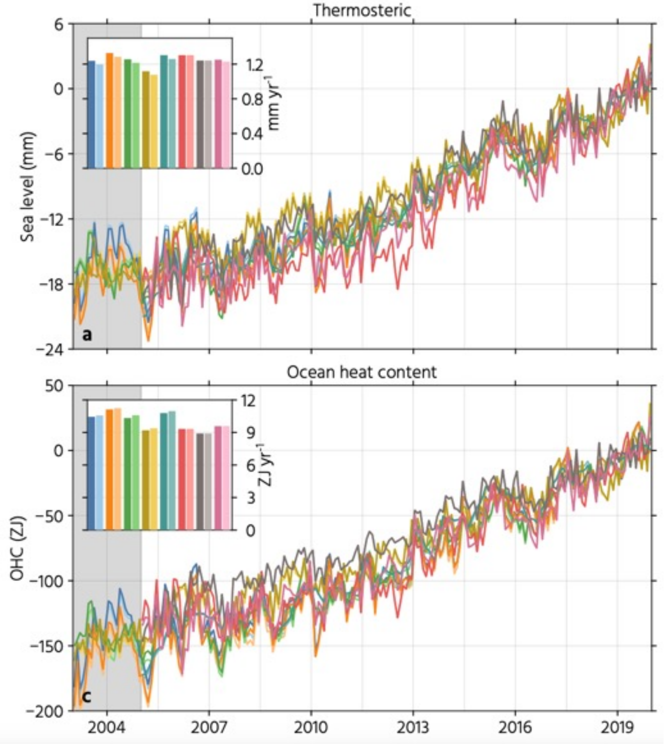
- **Taking Earth's heat inventory** (e.g. von Schuckmann et al., 2020)
  - In the global annual mean: $Net\ heat\ flux = heat\ storage + heat\ \cancel{transport}$
  - The world's oceans are the largest sink of heat (90%), followed by the land (5%), ice melt (3%), atmosphere (1%)

Ocean profiling is instrumental, but

Temperature, pressure, salinity through ocean column (0-2000m)
Temporal change in OHC (dOHC/dt) = ocean heat uptake (OHU)
OHU = 0.62 $\pm$ 0.1 Wm^{-2}; EEI = **0.77** $\pm$ 0.1 Wm^{-2} (2005-2019)
(including deep ocean & non-ocean heat uptake)

- In-situ systems largely miss deep ocean
- Spatio-temporal sampling is incomplete
- Comprehensive uncertainty analysis missing
- Independent approach to verify?





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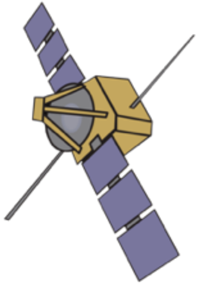

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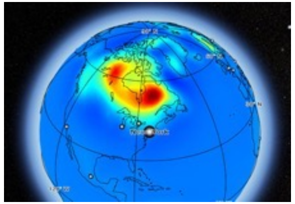
- EEI measurement from Space?
  - **Sea level budget using geodetic observations (indirect)**
  - Radiation pressure acting on LEO satellites (direct)

Sea level budget



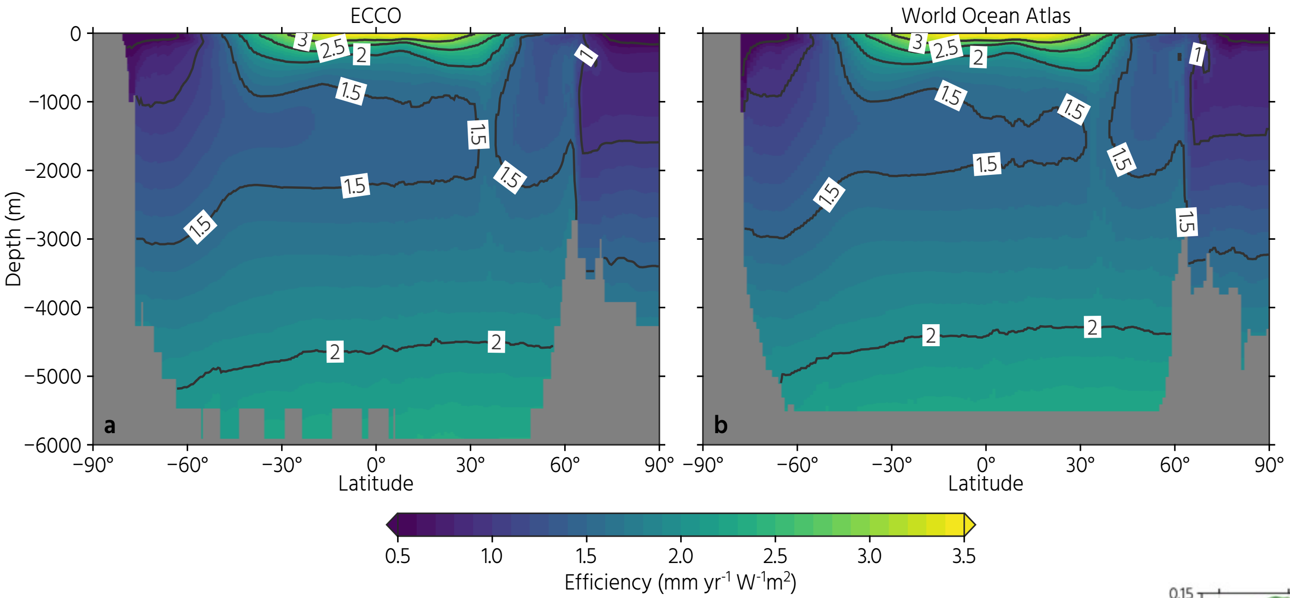
Total sea level change = Ocean mass change + Steric change (+ geophysical corrections)

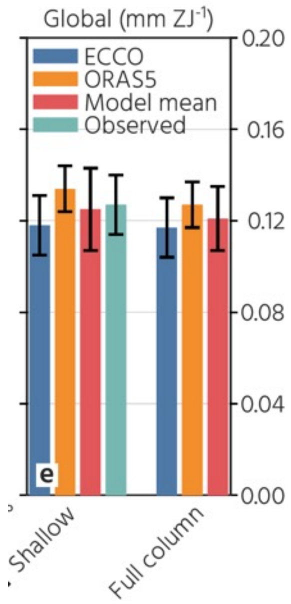
→ Thermal expansion (thermosteric change) = Total sea level change – Ocean mass change (+ geophysical corrections)

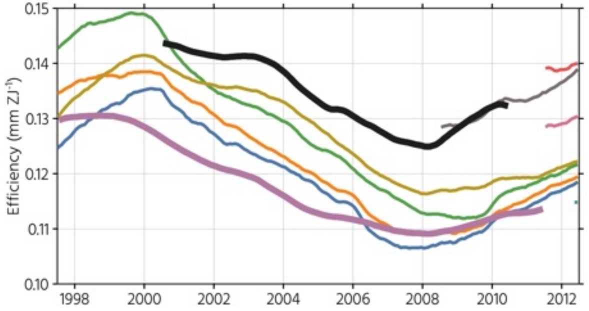
- **Altimetry:** Copernicus DUACS Delayed-Time DT-2018
- **GRACE and GRACE-FO:** Release 6 JPL GRACE and GRACE-FO mascon V02 solutions
- **Argo only and Argo + other in-situ (upper 2000m):** SIO, JAMSTEC, BOA, EN4, Ishii et al., Cheng et al., NOAA
- **Glacial isostatic adjustments + contemporary ocean-bottom deformation:** GIA prediction ensemble (Caron et al., 2018); GRD effects (Frederikse et al., 2017)
- **Large ensemble** approach provides robust central estimates plus uncertainties (90% CI).

How do we get from steric sea level change to ocean heat storage?

The ocean's expansion efficiency of heat ε



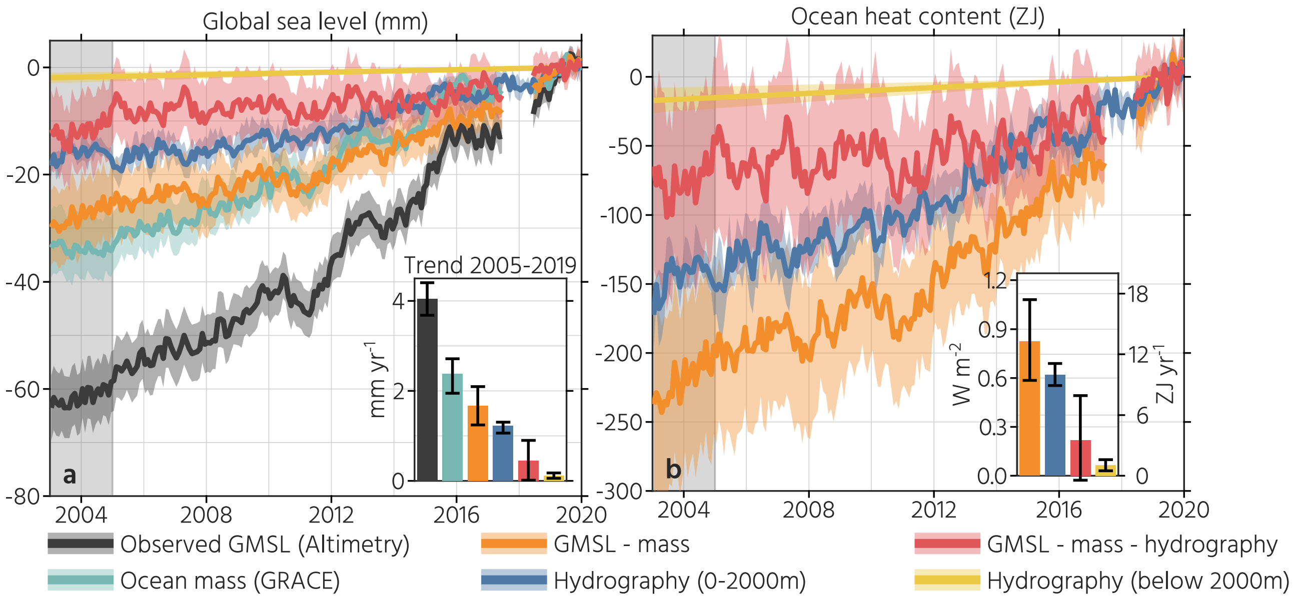




ε = 0.52 ± 0.1 $\mathbf{Wm^{-2}/mmyr^{-1}}$ (0.12 mm ZJ^{-1})

- Similar for both upper ocean (0-2000m) and full ocean column
- Time variability negligible?

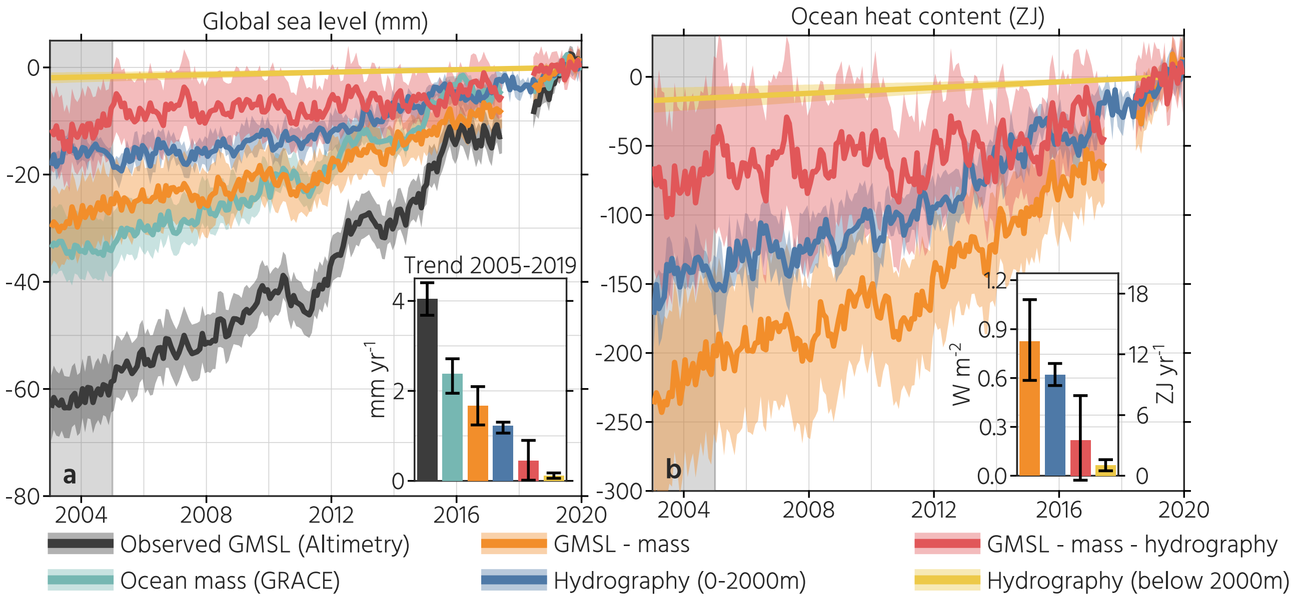
Sea level budget and *geodetic* ocean heat uptake



Steric sea level change = 1.67 ± 0.43 $mmyr^{-1}$ (geodetic) **OHU** = 0.86 ± 0.24 Wm^{-2}

OHU + non-oceanic heat uptake = **EEI = 0.94 ± 0.25 Wm^{-2}**

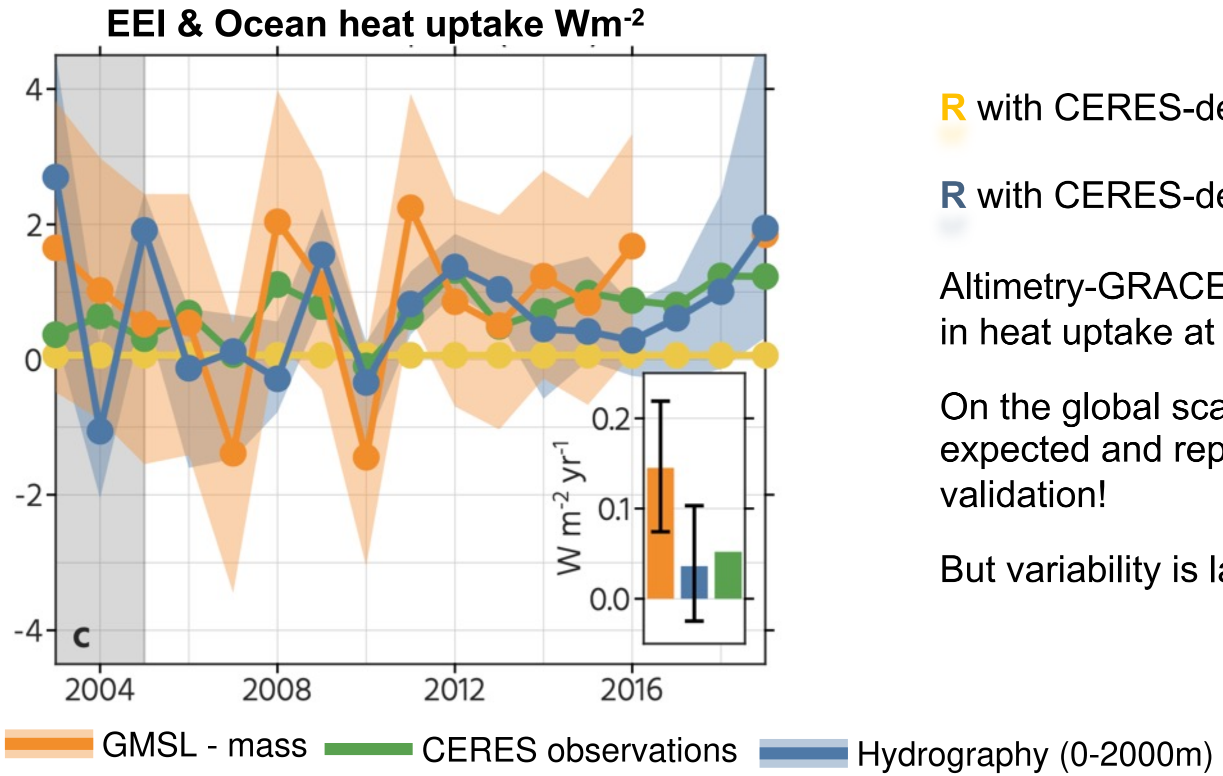
Sea level budget and *geodetic* ocean heat uptake



OHU geodetic – OHU in-situ = deep OHU?

Residual is 0.25 Wm^{-2} >> current knowledge (e.g. Desbruyer et al., 2016)

Time variability of EEI and ocean heat uptake (dOHC/dt monthly, then averaged to annual mean OHU)



R with CERES-derived EEI = 0.76

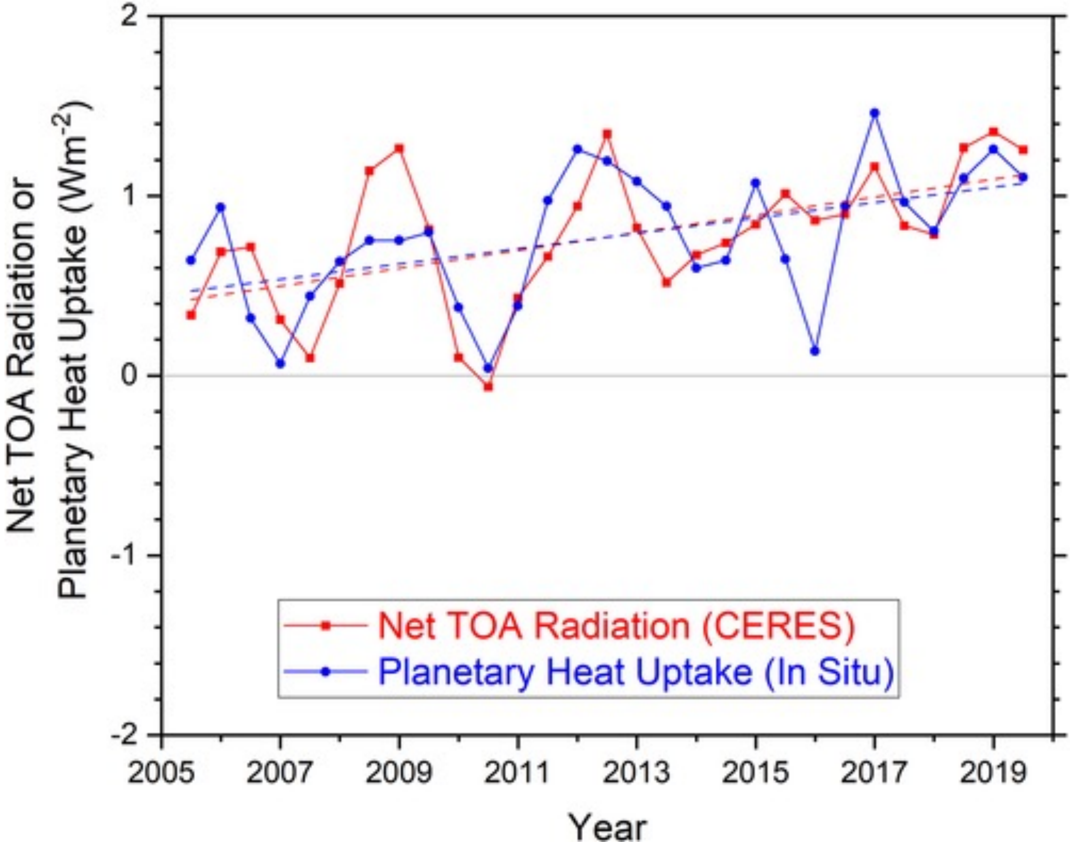
R with CERES-derived EEI = 0.30

Altimetry-GRACE and CERES suggest increase in heat uptake at 0.14 and 0.05 W $m^{-2}yr^{-1}$

On the global scale, this co-variability is expected and represents an additional form of validation!

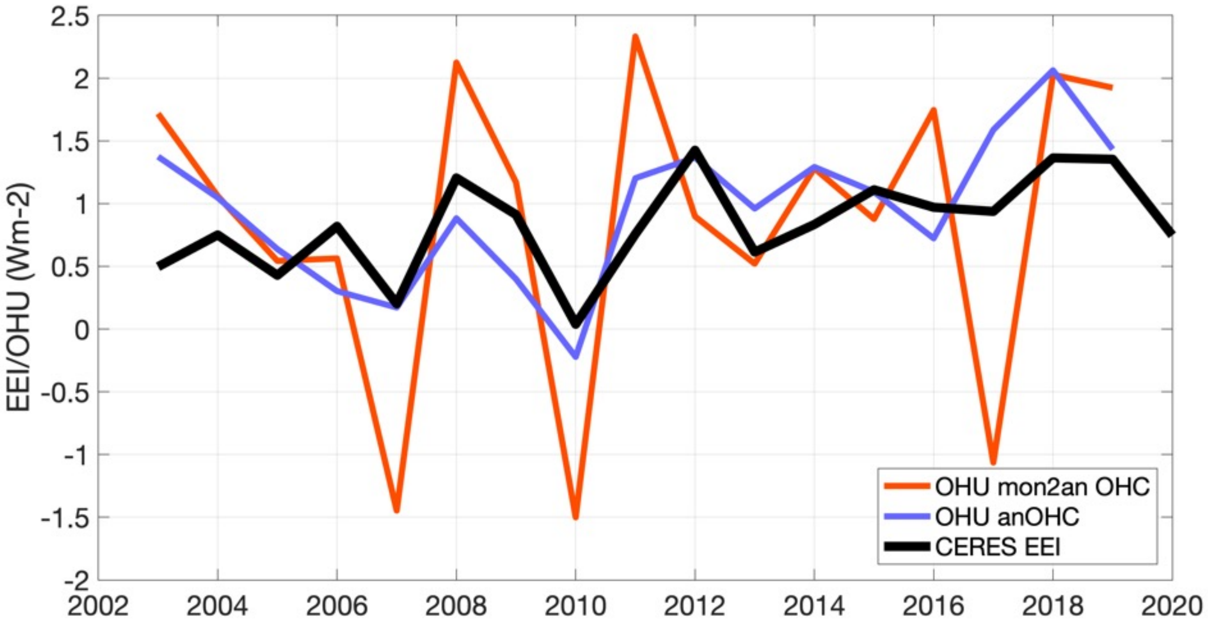
But variability is larger in ocean data?

OHU agrees well with CERES net flux when derived from annual mean OHC (here calculated at 6-months intervals):



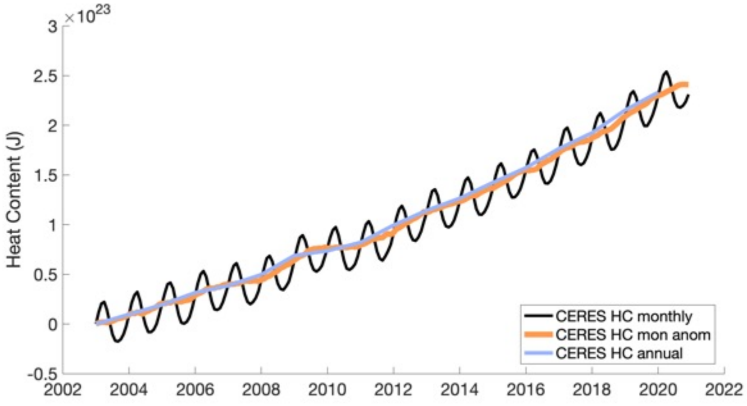
Loeb et al., 2021

Geodetic OHU variability decreases by more than 50% when derived from annual mean OHC…

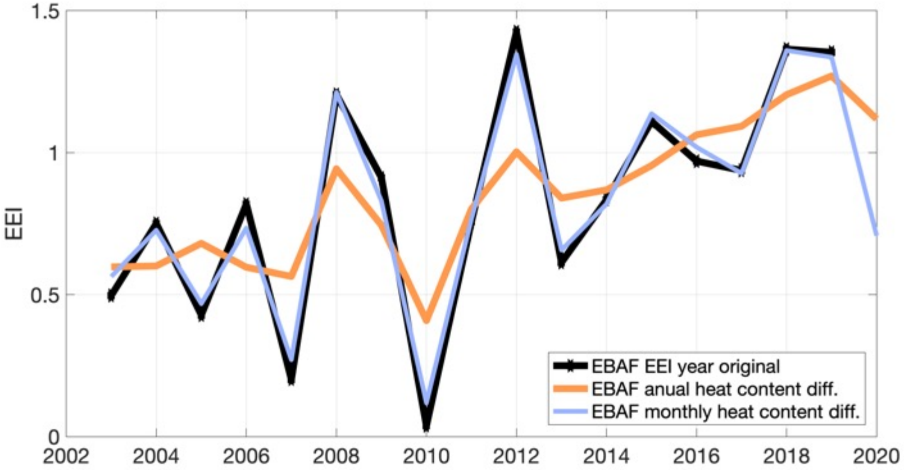


CERES surrogate analysis suggests OHU should be derived from monthly OHC to reproduce annual mean EEI variability:

Integrate monthly CERES EBAF net flux to heat content in J



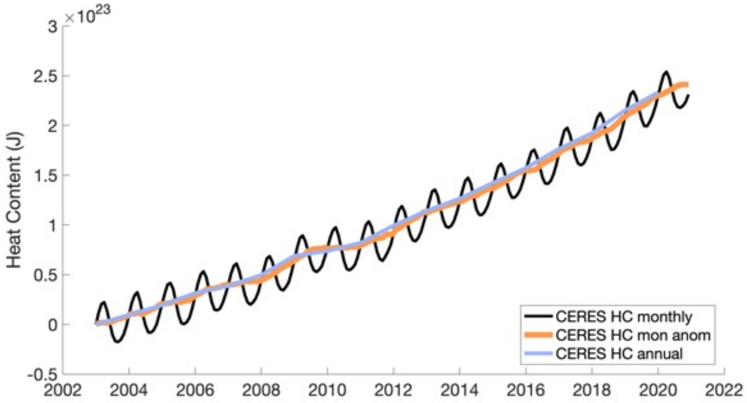
Derive EEI from monthly vs. annual mean heat content: monthly integration followed by annual averaging retains EEI variability



CERES surrogate analysis suggests OHU should be derived from monthly OHC to reproduce annual mean EEI variability:

Question remains: Which EEI variability is to trust? Can Libera shed light?

Integrate monthly CERES EBAF net flux to heat content in J



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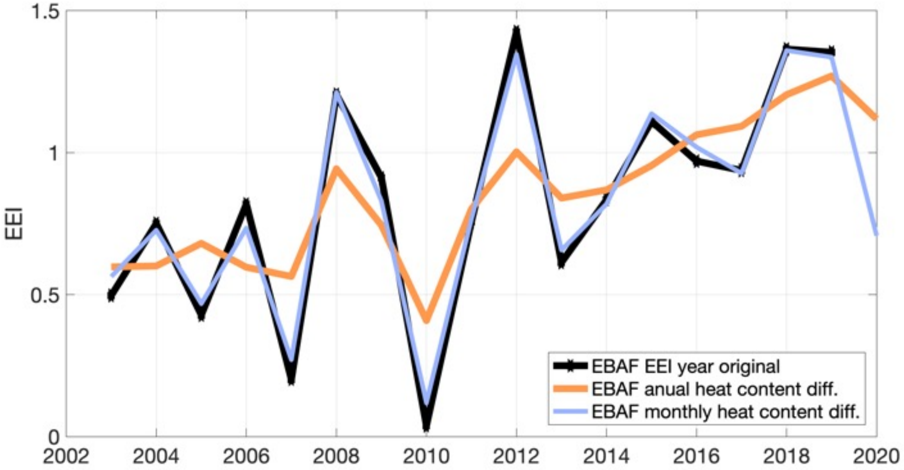


Can Libera improve estimates of EEI and its variability?

- Libera accuracy is more than doubled, but still not good enough to deduce absolute magnitude of EEI: +- 1.5 Wm^{-2}
- But can predicted radiometric improvements yield insight into realism of EEI variability?

Libera Instrument Requirements		
Parameters	**Performance**	**Predicted Performance**
Radiometer		
Field of view	25 km at nadir	24 km at nadir
Cross-track width	Limb-to-Limb	Limb-to-Limb
Spectral range	**LW**: 5-50 µm **SW**: 0.3-5 µm **TOT**: 0.3->100 µm	**LW**: 5-50 µm **SW**: 0.3-5 µm **TOT**: 0.3->100 µm
Radiometric Accuracy	**LW**: 0.5%, **SW**: 1% **TOT**: 0.5%	**LW**: 0.24%, **SW**: 0.17%, **TOT**: 0.22%
Radiom. stability	0.3% / decade	<0.1% / decade
Radiometric Precision	**LW**: <0.45 $Wm^{-2}sr^{-1}$ **SW**: <0.2 $Wm^{-2}sr^{-1}$ **TOT**: <0.3 $Wm^{-2}sr^{-1}$	**LW**: 0.11 $Wm^{-2}sr^{-1}$ **SW**: 0.11 $Wm^{-2}sr^{-1}$ **TOT**: 0.11 $Wm^{-2}sr^{-1}$
Linearity	<0.15% over dy-namic range	<0.1% over dy-namic range
Scanning mode	Cross-track	Cross-track, azimuthal

Conclusions

- We estimate ocean heat uptake using total sea level and ocean mass observations and yield an EEI larger than from hydrography.
- Larger EEI is supported by few other studies, e.g. using ocean reanalysis (Trenberth et al., 2016; 2020) or changes in atmospheric composition (Resplandy et al., 2019).
- Sea level budget is only barely closed in recent years and requires reevaluation of all data products.
- EEI is increasing: global warming is accelerating
- Co-variability between CERES and OHU is given, but amplitude mismatch is under investigation – likely a result of OHU derivation

Back up

Efficiency effect

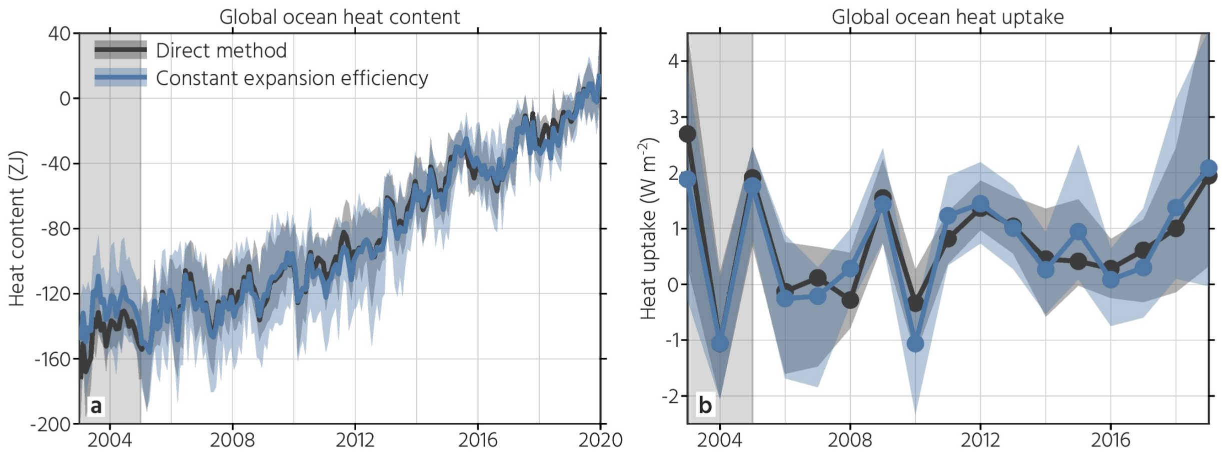
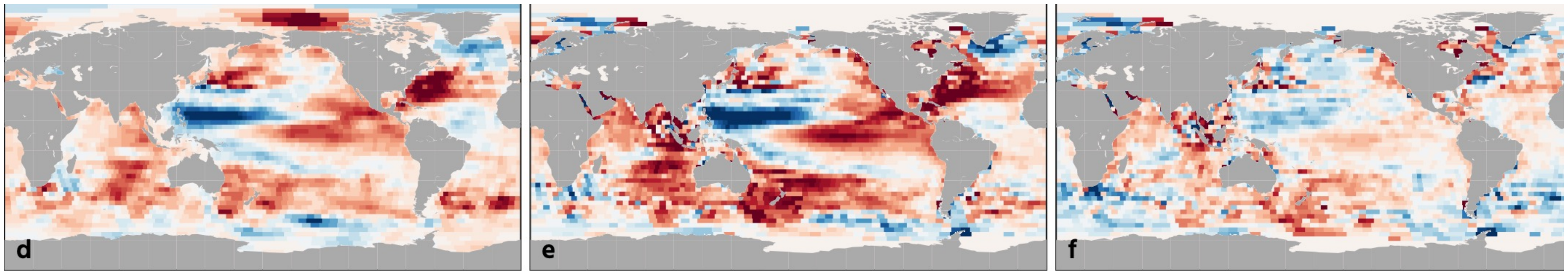
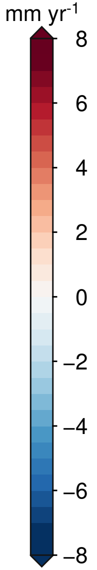


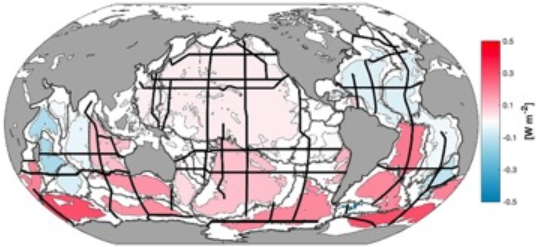
Figure S4. The effect of assuming a constant expansion efficiency on OHC and OHU estimates. Panel a. OHC and panel b. OHU. The black line shows the direct estimate of OHC and OHU from hydrographic observations. The blue line shows the estimated OHC and OHU using the steric changes estimated from hydrography converted to OHC and OHU using a time-mean expansion efficiency of 0.13 +/- 0.01 ZJ yr-1

Regional sea level budget

Upper ocean steric change (in-situ) **Full-column steric (geodetic)** **Residual = deep ocean steric (?)**





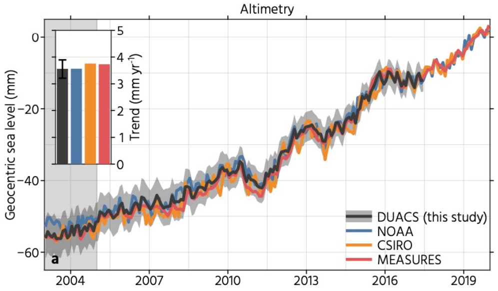


- Residual steric expansion mainly in Indo-Pacific
- Pattern of positive deep steric changes is unrealistic; cannot be explained by deep OHS alone
- This large deep OHS (0.25 Wm^{-2} compared to 0.06 in-situ) is unlikely.

(Meyssignac et al., 2019)

“Non – closure” of the global sea level budget

- … results in a larger EEI = 0.94 Wm^{-2} (geodetic; in-situ = 0.76 Wm^{-2})
- Discrepancy to in-situ estimates is unlikely due to enhanced deep OHS and is increasing in recent years
- Other unlikely sources of error:
  - Ocean mass budget is closed
  - Altimetry is reliable
  - Geophysical corrections are state-of the art and physically necessary. Uncertainties are incorporated in sea level estimate: 4.05 **[3.68 4.40]** $mmyr^{-1}$.
- Previous studies find tighter closure, but over different time period, using outdated GRACE solutions and geophysical corrections.
- No obvious error source: EEI might be larger than expected from perspective of *geodetic* sea level budget approach
- In-situ sampling and mapping techniques may explain some of the discrepancy



Why do we need to know EEI?

- **Global Climate Model "tuning"**
  - Goal: Stable PI climate at global mean temperature of ~14 deg C
  - Tuning target: Observed long-term global mean TOA fluxes
- **Adjusting observed TOA radiation fluxes**
  - Calibration & algorithms introduce large uncertainty in EEI of +- 4 Wm^{-2}
  - Target: Observed long-term global change in planetary heat content
- Estimating and constraining Climate Feedback parameter requires high accuracy EEI variability